Fully Braced for Seismic Survival

Osaka convention center engineer used a supercomputer to simulate quake scenarios

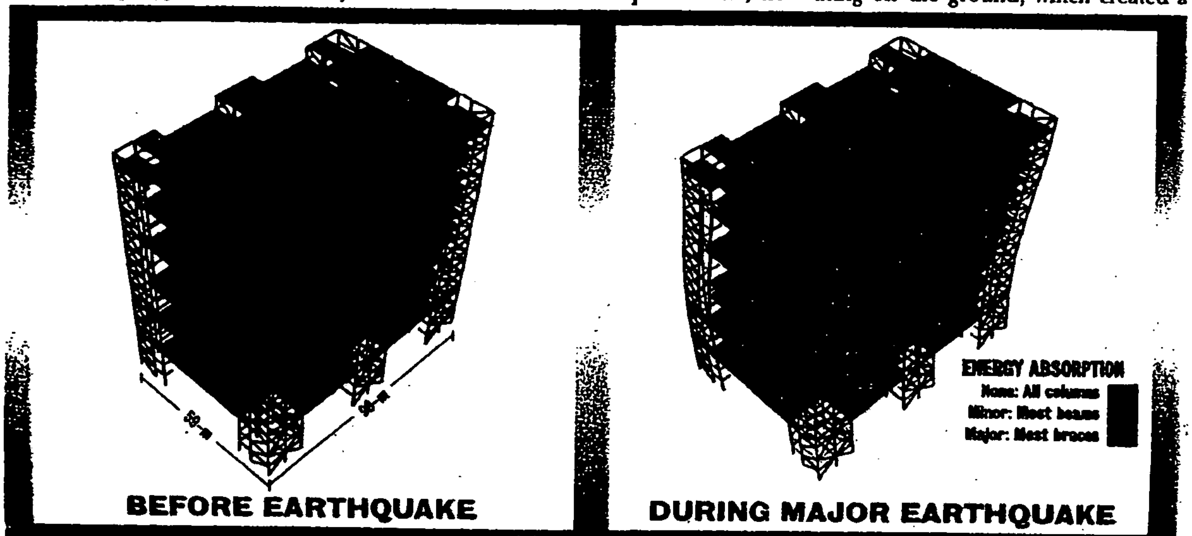
A supercomputer and software normally used for auto body collision analysis took every structural component of Osaka's emerging $420-million-plus convention center through numerous simulations of earthquakes likely to hit that part of Japan. The 104-meter-tall building, set for completion in 2000, is raised above a ground-floor plaza, has a cavernous auditorium half way up and is close to a geological fault. But with its intensively engineered system of shock-absorbing braces, the designers are confident of the 13-story steel frame's seismic survival.

A 10-company joint venture led by Takenaka Corp., Osaka, began three years of work on the building's $298-million general contract last November. Before the contractors could start building the six structural cores and story-deep trusses, which are the center's frame, the designers had to demonstrate exactly how the structure would respond to quakes. That was a requirement of Japanese "damage-tolerant design," which sacrifices special braces to leave the rest with little damage.

"The Japanese are interested in using intelligent systems," says Ted Piepenbrock, a Californian who heads the job's seismic team at Ove Arup & Partners, the project's London-based structural engineer. "The U.S. has a completely different approach but it's changing."

At Osaka, "for every single beam, column and brace, we had to make sure that it satisfied the [seismic] performance criteria," Piepenbrock continues. That meant using three-dimensional, nonlinear, finite-element, time-history analysis. "You could not have gotten approval otherwise," he says.

Kisho Kurokawa Architects and Associates, the building's Tokyo-based designer, put the 67,000-sq-m high-rise on 13 floors and, except for the cores, raised the whole thing off the ground, which created a



SACRIFICIAL Diagonal unbonded braces (red) will be sacrificed in an earthquake to allow main structural frame to stand.

"hollowed-out" base for a public plaza. "There is a lack of open space in downtown Osaka. The citizens...strongly requested a plaza," says Kurokawa.

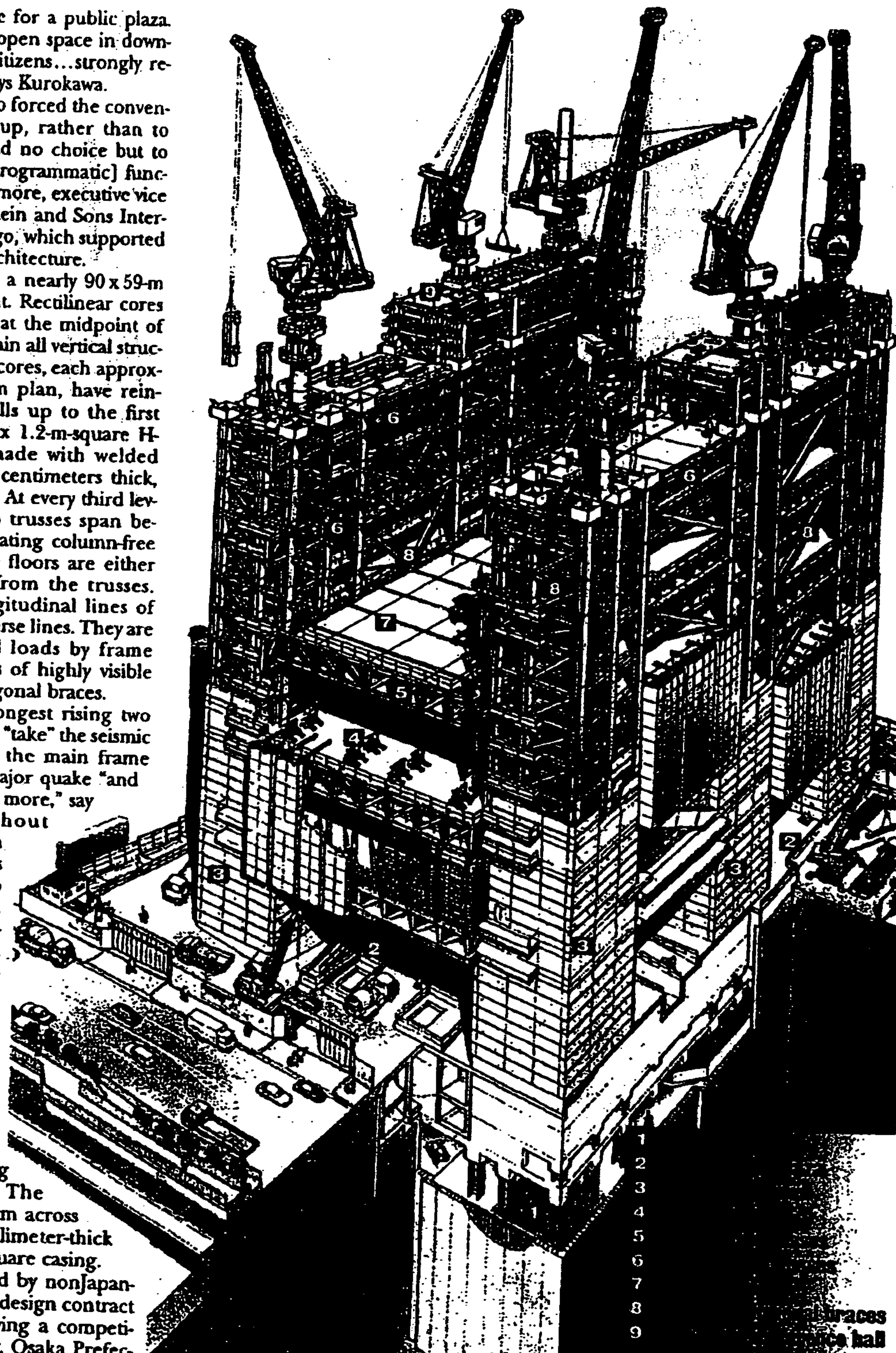
Lack of space also forced the convention center to go up, rather than to spread out. "We had no choice but to stack the various [programmatic] functions," says Mike Damore, executive vice president of A. Epstein and Sons International Inc., Chicago, which supported Kurokawa on the architecture.

The building has a nearly 90 x 59-m rectangular footprint. Rectilinear cores at each corner and at the midpoint of both long sides contain all vertical structural elements. The cores, each approximately 14 x 12 m in plan, have reinforced concrete walls up to the first floor. Above that, six 1.2-m-square H-section columns, made with welded steel plates up to 8 centimeters thick, continue to the roof. At every third level, single-story-deep trusses span between the cores, creating column-free spaces. Intermediate floors are either hung or propped from the trusses. There are four longitudinal lines of trusses and six transverse lines. They are stiffened for lateral loads by frame action and hundreds of highly visible energy-absorbing diagonal braces.

The braces, the longest rising two floors, are designed to "take" the seismic damage and protect the main frame during at least one major quake "and probably two or three more," say the designers. Without buckling, they can stretch and compress under cyclic loads, into the yield zone. Each brace has a cross-shaped section and is covered with debonding chemicals so that it can slip freely inside a concrete-filled steel casing.

Not connected to the main frame, the concrete and casing prevent the unbonded brace from buckling without stiffening it. The biggest braces are 55-cm across and made with 36-millimeter-thick steel, inside a 65-cm-square casing.

Kurokawa, supported by nonJapanese specialists, won the design contract three years ago, following a competition held by the owner, Osaka Prefecture. "It's an international facility, so I



STACKED Lack of open space downtown meant a "vertical" convention center.

thought a Japanese-American-British collaboration would be interesting," says Kurokawa. He had asked Epstein for advice on the basis of its work at Chicago's McCormick Place, the world's largest convention facility. "It was quite exciting for me to introduce their know-how of [U.S.-style] convention functions," adds Kurokawa.

And he had also recruited Arup, having worked with the firm on various projects. Arup moved to Tokyo in the 1980s mainly to get work on Japanese projects in third countries, says Philip Dilley, a London-based director of Arup. Then, "there was the phase of big-name international architects working in Japan and we came in on the back of those. The biggest job—Kansai airport—put Arup on the map, he adds. With about 20 local jobs behind it, Arup is the only foreign engineer registered as a firm to practice in Japan.

In January 1995, well into the work, the Kobe earthquake struck. The poor performance of some Kobe buildings prompted design changes, says Arup. For example, at Kobe, "there was a building with a similar steel structure...which had brittle failure. Columns just snapped," says Joop Paul, Arup's project coordinator. "Prior to the earthquake we had never heard of such failure."

To alter the Osaka design based on Kobe, the engineer modified the steel specification and reduced the amount of welding, partly by replacing box shaped columns with the H-sections.

TOLERANCE For seismic analysis, Arup had to comply with Japanese criteria for damage tolerance. As the Osaka structure is over 60 m in height, special approval is needed from the Tall Buildings Committee. The approval process calls for performance-based seismic design from first principles. And it requires nonlinear analysis, both static and dynamic, under seismic loading.

To do all that, Arup dipped into its Advanced Technology Group, staffed by mechanical and stress engineers. With access to a Cray supercomputer, the group has modeled collision impacts on cars, trains and even nuclear fuel flasks by running LS-DYNA, "one of the most advanced nonlinear dynamic analysis programs in the world," says Piepenbrock. Sitting with the group, the building seismic team can exploit all that computer power.

While most building designers are "ramping up" software to model increasingly complicated structural behavior, Arup is "toning down" its DYNA program, he adds. The firm is almost alone in "using explicit time-integration techniques in nonlinear seismic analysis for buildings," claims Piepenbrock.

EXPLICIT Nonlinear finite-element analysis in building construction normally uses simplified "implicit" methods with a relatively small number of complex calculations. The explicit technique, used at the Osaka center, runs many more but simpler calculations. The much-more-frequent calculations demand large computers. But with modern software, "I can build huge complex models very quickly and analyze the results very quickly," Piepenbrock explains.

For the Osaka building, the 3D computer model had over 10,000 nonlinear elements representing inelastic behavior in every structural component. Arup analyzed the building three dimensionally, and also with ground motions in three directions because the long floor trusses would experience effects of gravity, as well as horizontal and vertical shaking. The analysis had to be nonlinear to determine the inelastic behavior of all structural components, and to demonstrate that the primary frame would not yield.

Nonlinear work started with typical Japanese building push-over modeling under static loads to determine lateral force/deflection characteristics for each story. Normally, push-over data would be used in simplified one-dimensional nonlinear analysis of the building. It was not strictly needed for the Osaka job, where every structural element was then modeled in three dimensions under simulated ground displacements and velocities using the DYNA software. This kind of analysis provides the data on damage and energy dissipation throughout a building, which is needed for Japan's damage-tolerant designs.

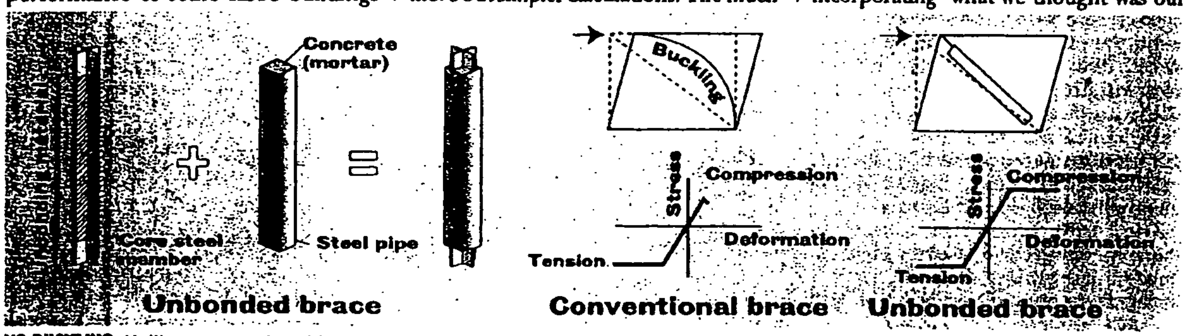
Japanese engineers protect columns and beams with their special braces. But the U.S. approach encourages seismic energy to dissipate in the main gravity load-resisting elements, such as beams in moment frames, and eccentric-braced-frame link beams, says Piepenbrock. "U.S. building codes have not encouraged designers to quantify damage to these elements," he says.

But since California's 1994 Northridge earthquake, U.S. seismic design philosophy has begun to change, adds Piepenbrock. At Northridge, over 100 buildings incorporating "what we thought was our best system" performed badly, he says. Now, with the Structural Engineers Association of California also developing and promoting performance-based design, Piepenbrock believes U.S. and Japanese approaches are beginning to converge.

ALLOWABLE The new Californian approach moves away from prescribing seismic design forces in favor of recommending allowable inelastic deformations of frame components. "For an economical design, the building's strength may be exceeded and we must rely on providing displacement capacity," says Piepenbrock.

Requiring greater engineering skills and resources, the new approach has its detractors. But shocking events at Kobe and Northridge "really have begun to change the way engineers design and analyze buildings," maintains Piepenbrock. "We no longer accept that damage could be anywhere in a building....We can do much better than that." ❑

By Peter Reina with Dennis Normile



NO BUCKLING Unlike conventional braces that buckle, unbonded braces will stretch and compress under seismic loads.